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Irrigating Forage Crops with Saline Waters: 1. Volumetric Lysimeter Studies

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ABSTRACT

In regions lacking outlets for agricultural drainage disposal, the recycling of drainage waters for irrigation is increasingly seen as a viable management option. Vadose zone modeling could potentially assist in the design of management practices for drainage reuse operations, but data are lacking about the accuracy of simulations of root water uptake under the dynamic, saline field conditions that are encountered in reuse systems. This study used a volumetric lysimeter system to examine, within the context of drainage reuse management systems, relationships between irrigation water salinity, irrigation depth, forage crop biomass production (alfalfa [*Medicago sativa* L.] and tall wheatgrass [*Agropyron elongatum* (Host) P. Beauv.]), ET (evapotranspiration), drainage depth, and drainage water quality. Findings include: (i) ET rates in the volumetric lysimeters were very high owing to clothesline and oasis effects; (ii) the relationship between ET and yield differed from what has been reported in the literature, possibly due to higher evaporation rates in abundantly watered, salt-stressed treatments that had reduced canopy cover; (iii) the salt tolerance exhibited by tall wheatgrass was significantly lower than what has been reported in the literature, whereas the salt tolerance of alfalfa was found to be in reasonably good agreement with reported values; (iv) leaching fractions varied greatly in response to both irrigation depth and irrigation water quality; and (v) drainage water quality and depth varied in response to temporal variations in evapotranspiration. In a companion study, the data were evaluated against a simulation model considered for use in the design of reuse management practices.

The future of irrigated agriculture is threatened by increasing water scarcity and the ancient problems of water-logging, salinization, and degraded soil and water quality (Postel, 1999). Developing innovative and more efficient agricultural water management is essential to developing sustainable irrigation. In particular, improved drainage and salt management is crucial—the conventional practice of disposing of saline drainage waters into surface waters or onto lands is a leading source of salinization and degraded soil and water quality.

With many operational variables to consider, developing improved water and salt management practices using trial and error in the field may prove difficult and time consuming. Modeling offers a cost-effective means of accelerating the development of innovative management practices. Vadose zone models such as HYDRUS (Šimůnek et al., 1998), SWAP (van Dam et al., 1997), and UNSATCHEM (Šimůnek et al., 1996) are capable of simulating a wide range of management scenarios and provide detailed computations of soil and drainage conditions.

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One impediment to more widespread acceptance and use of modeling in the design and analysis of management systems is a lack of information on the accuracy of model simulations. Some potential users of simulation models question whether simulations are sufficiently accurate representations of what occurs in the field, particularly given the substantial parameter uncertainty that will inevitably occur in routine field applications. The data needed to address these concerns are not currently available, nor are they easy to obtain.

As an example of an agricultural management practice that could benefit from modeling, consider agricultural drainage reuse operations. In some instances, the impacts of agricultural drainage disposal may be reduced if drainage waters are isolated and reused for irrigation (Rhoades, 1989, 1999; Rhoades et al., 1992). During the last 25 yr, the recycling of drainage water for irrigation has been examined in several experiments and demonstration projects (Oster and Wichelns, 2003; Rhoades et al., 1992). Most projects have followed either a sequential or cyclic reuse strategy. With the sequential strategy, a crop with low or moderate salt tolerance is grown in Field A using the highest quality water that is available. Drainage water is collected from Field A and used to irrigate a salt-tolerant crop in Field B. The process may be repeated, with drainage from Field B used to irrigate a salt-tolerant crop in Field C, and so on. At the final stage, drainage water from the last field is diverted to an evaporation pond or otherwise disposed of. A similar idea is employed in the cyclic strategy, except that rotations of irrigation waters and crops are done on a single field during consecutive growing seasons.

With either reuse strategy, water is lost to ET at every stage, so the drainage volume from the last stage is smaller and more concentrated than at the first stage. Where drainage disposal is restricted or expensive, the reduction in disposal costs is expected to offset the cost of committing land to salt-tolerant crops that may not have great profit potential. Scientific and economic questions remain about the management of reuse systems and the suitability of different waters, soils, and crops for reuse operations (Rhoades, 1999). Answering these questions requires an understanding of how salts affect waters, soils, and plants, and how irrigation and drainage management can be used to affect these relationships and achieve land management and economic goals (Rhoades, 1999).

Of course, the effects of salts on plants, soils, and waters have been studied intensively for many decades. But with drainage reuse programs, one must consider the effects of irrigating with poorer quality water than what

Abbreviations: DOY, Day of Year; EC, electrical conductivity; ET, evapotranspiration.

traditionally has been considered agronomically viable. Furthermore, the economics of reuse systems depends crucially on the water balance at each stage (Kan et al., 2002; Knapp, 1999), so the precision with which drainage and root water uptake (or ET) can be estimated is perhaps more important than in the past.

Rhoades (1999) reviewed steady-state model calculations that demonstrate the basic conceptual soundness of drainage reuse programs, and noted that while more comprehensive model calculations are desirable, they are not yet justified because of insufficient evidence documenting the accuracy of more comprehensive numerical models. Indeed, the root water uptake functions found in many advanced simulation models have not been extensively evaluated against experimental data, especially across the range of field conditions that may be encountered in a reuse system. The recent work of Homaee et al. (2002) is one of the few studies comparing (greenhouse) measurements with model (HYSWASOR) calculations of root water uptake under combined, transient salinity and water stresses.

Commonly, root water extraction is modeled by introducing a sink term into the Richards equation. In general, the sink may be a function of rooting depth and density, atmospheric variables (potential ET), and soil water potential (matric and osmotic). Various parameterized forms for the sink term have been developed over the years, including reduction functions that specify the uptake reduction that occurs when there are osmotic or drought stresses (Feddes and Raats, 2004). It has been proposed (e.g., van Dam et al., 1997; van Genuchten, unpublished data, 1987; Feddes and Raats, 2004) that uptake reduction parameter values for different crops can be derived from literature studies of whole-plant response to drought and salinity stress, particularly tabulations of plant salt tolerances.

Using a newly constructed volumetric lysimeter system, our objective was to examine, within the context of drainage reuse management systems, relationships between irrigation water salinity, irrigation depth, forage crop biomass production (alfalfa and tall wheatgrass), ET, drainage depth, and drainage water quality. In a companion study (Skaggs et al., 2006), we modeled the data using the HYDRUS simulation code, analyzing especially the parameters required to simulate reductions in root water uptake occurring in response to salinity and drought stresses.

The data presented here should be of interest to those operating or designing reuse systems, and to those developing models that account for salinity and drought stresses. Additionally, by providing a detailed exposition of experimental procedures and measured data, we aim to shed light on the assumptions and approximations that are implicit in the idea of deriving uptake reduction parameter values from salt- and drought-tolerance tables. The experimental trials on which such tables are based frequently use nonstandard growing conditions, and many times key experimental variables are only roughly approximated and not actually measured. These facts, it seems, are not always fully appreciated by the modeling community.

METHODS AND MATERIALS

Volumetric Lysimeter System

The outdoor lysimeter system used in this study is located at the George E. Brown, Jr., Salinity Laboratory (USDA-ARS) in Riverside, CA, and consists of 24 volumetric lysimeters, each measuring 81.5 cm wide by 202.5 cm long by 85 cm deep. The lysimeters are above ground and constructed with 20-cm-thick concrete walls. The ground between and surrounding the lysimeters is covered with rock and concrete, creating a relatively dry, advective environment. Under such conditions it is common for lysimeters to exhibit both "clothesline" and "oasis" effects (Allen et al., 1998), leading to high ET rates relative to standard growing conditions.

The lysimeters are filled with Lytle Creek (CA) river sand (96% sand, 3% silt, 1% clay) to a depth of 80 cm. The sand has a high saturated hydraulic conductivity (>500 cm d^{-1}) and limited cation exchange capacity, a setup that is commonly used in plant salt-tolerance trials because it simplifies experimental control of the soil water chemistry. Each lysimeter is equipped with a neutron probe access tube.

An adjacent, below-grade structure houses 24 irrigation water reservoirs. Each 1740-L reservoir is connected to one lysimeter via 5-cm PVC (polyvinyl chloride) pipe. Electric pumps transfer water from the reservoirs up to the lysimeters, where it is discharged through perforated 2-cm PVC pipes lying on the soil surface. Irrigation is rapid, with the desired water volume being applied to the lysimeter surface within a couple of minutes.

The concrete bottom of each lysimeter is sloped so that drainage is directed to a shallow trench running lengthwise down the center of the lysimeter. A 5-cm perforated polyethylene drainpipe is installed in the trench. The drainpipe empties into a second 5-cm PVC line that carries drainage by gravity flow back to the irrigation reservoir. Drainage water is therefore recirculated through the system (Fig. 1). Just before the drainage line empties back into the irrigation reservoir, the water flows through a small 2.4-L container that spills over into the larger reservoir. The electrical conductivity of the water in the small container (i.e., the drainage water) is monitored with a four-probe instrument connected to an automated data acquisition system. Likewise, a calibrated pressure transducer installed at the bottom of each irrigation reservoir monitors the height of the water in the reservoir (Fig. 1), with

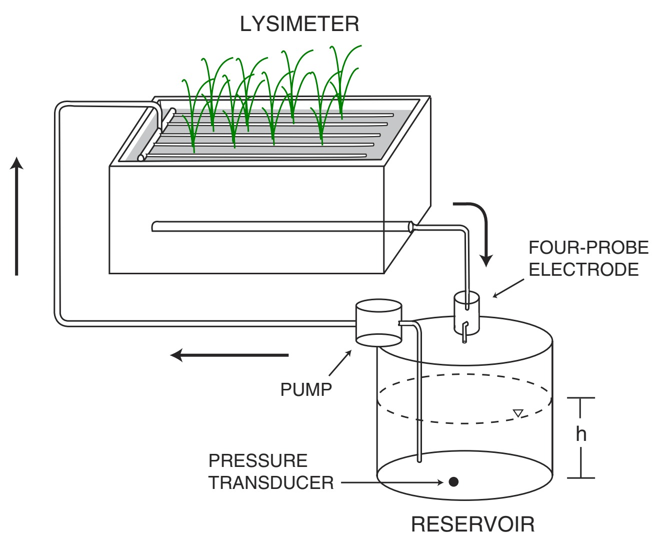

Fig. 1. Schematic diagram of a volumetric lysimeter. The experiment was conducted in a facility consisting of 24 lysimeters.

measurements logged every 6 min. As water is lost from the system by ET, the irrigation reservoirs are periodically refilled and checked to ensure that the chemical composition of the irrigation water is maintained. Details about the electronics and instrumentation in the lysimeter system can be found in Poss et al. (2004).

The operating principle of the recirculating, volumetric lysimeter system is that irrigation, drainage, and ET can be calculated based on (nearly continuous) measurements of the height of the water in the reservoir at time t, $h(t)$. Figure 2 illustrates the basic idea. A sudden decrease in h indicates irrigation, and the irrigation depth can be calculated from the change in the height, Δh, and the cross-sectional areas of the reservoir and lysimeter. If subsequent lysimeter drainage occurs, h rebounds due to the return flow and eventually levels off when drainage ceases; the drainage depth can be calculated from the height of the rebound. A sudden jump in h occurs with the addition of new water to the reservoir.

Evapotranspiration is calculated based on the difference between irrigation and drainage depths. During a given time interval, water balance requires

$$\mathrm{ET} = I + P - D - \Delta S \quad [1]$$

where ET is evapotranspiration (cumulative during the time interval), I is irrigation (cumulative), P is precipitation (cumulative), D is drainage (cumulative), and ΔS is the change in stored soil water, S. Neutron probe measurements of soil water content at multiple depths can be used to estimate S, but the estimate may not be very precise as it requires an uncertain interpolation between neutron measurements, which are themselves water content estimates averaged for an uncertain soil volume. Additionally, when the sand lysimeters are irrigated with high frequency (e.g., every other day), S will not change very much day to day, and calculating ΔS by difference may further degrade the precision of the ΔS estimate (subtraction of two nearly equal numbers). Consequently, during short time intervals (e.g., a few days), Eq. [1] is not effective for calculating ET because the error or uncertainty in ΔS can be of the same order of magnitude as both ΔS and ET.

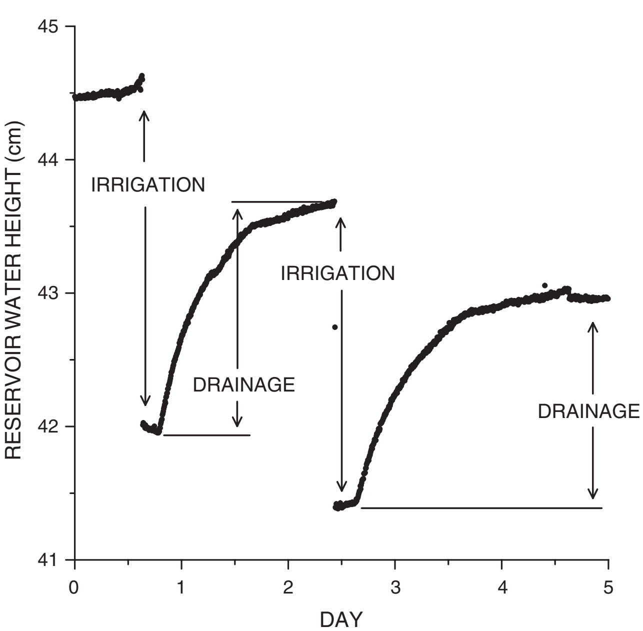

Fig. 2. Illustration of the calculation of irrigation and drainage depths based on measurements of reservoir water height.

For longer time periods (e.g., 30 d or more), ΔS becomes an increasingly insignificant component of ET, and a good approximation is

$$\mathrm{ET} \sim I - D \quad [2]$$

where P is either negligible or absorbed into I. Equation [2] has the obvious benefit of not requiring labor-intensive neutron probe measurements. Additionally, considering the lack of precision with which ΔS can be determined in the volumetric lysimeter system, it can be argued that Eq. [2] provides an estimate of ET that is no less precise than that given by Eq. [1].

Experimental Design and Procedures

For drainage reuse systems in California's San Joaquin Valley, salt-tolerant forage crops are among the crops considered to have the greatest economic potential (Robinson et al., 2004; Grattan et al., 2004a). Two forage crops were used in this study: 'Salado' alfalfa and 'Jose' tall wheatgrass. In an earlier greenhouse study, these cultivars were identified as good candidates for drainage reuse operations, exhibiting high salt tolerance, biomass production, and forage quality when grown under saline–sodic conditions (Robinson et al., 2004; Grattan et al., 2004a, 2004b; Grieve et al., 2004). On 14 Nov. 2001, 12 lysimeters were planted in alfalfa and 12 in tall wheatgrass. For several months, all lysimeters were abundantly irrigated with good quality (low electrical conductivity), nutrient-rich irrigation water. During this period of crop germination and establishment, the alfalfa and wheatgrass were harvested (cut by hand to a canopy height of 10 cm) several times (alfalfa on 25 Feb., 5 Apr., and 1 May 2002; wheatgrass on 25 Feb., 20 Mar., 12 Apr., and 1 May 2002).

The experimental treatments started on 2 May 2002 (DOY [Day of Year] 122) and proceeded in two phases. In the first phase (DOY 122–237), the crops were irrigated with synthetic drainage waters of varying salinities, ranging from 2.5 to 28 dS m^{-1}. The chemical compositions of the irrigation waters are given in Table 1; the experimental treatments are summarized in Table 2. There were two replicates of each treatment during this phase. All lysimeters were well watered, so only salinity stress was imposed (no drought stress). In addition to the constituents listed in Table 1, nutrients were added such that nutrient availability was not expected to limit growth. The alfalfa was harvested on DOY 143, 171, 191, 220, and 241; the wheatgrass on DOY 143, 164, 190, 220, and 241.

Phase 1 was followed by ~10 d of high-frequency, high-volume irrigations intended to leach the sand of any salts that accumulated during Phase 1. Lysimeters were irrigated with the same waters used in Phase 1.

Phase 2 (DOY 247–297) commenced immediately thereafter using the same irrigation waters (Table 1) and irrigation frequency (every other day); however, as shown in Table 3, lysimeters were irrigated with a prescribed fraction (f = 0.5, 0.75, 1.0, or 1.25) of the ET measured in two lysimeters (one wheatgrass, one alfalfa) identified as "controls." The control lysimeters were abundantly irrigated with 2.5 dS m^{-1} water. Using Eq. [2], we maintained running calculations of ET for these lysimeters. On irrigation days, the other lysimeters were irrigated with their prescribed fraction f of the ET that was calculated for their respective control. So, for example, if the running ET calculation for the alfalfa control showed that ET since the last irrigation was 8 mm, then the f = 0.5 alfalfa treatment would receive 0.5 × 8 mm = 4 mm of water, the f = 0.75 treatment would receive 6 mm, and so on. Thus lysimeters with $f < 1$ received less water than was being consumed in the well-watered control (deficit irrigation), whereas lysimeters

Table 1. Chemical composition of irrigation waters used in the study.

Electrical conductivity	Ca^{2+}	Mg^{2+}	Na^{+}	SO_4^{2-}	Cl^{-}
dS m^{-1}	mol m^{-3}				
2.5	2.5	1.5	13.8	7.0	7.0
8.0	8.2	6.5	58.2	29.6	28.2
13.0	12.9	11.4	100.7	49.7	48.8
18.0	13.5	17.8	157.5	71.4	76.4
23.0	13.6	24.3	215.6	93.5	98.4
28.0	14.0	27.8	281.9	117.5	126.4

with $f \geq 1$ received water equal to or in excess of that amount. Treatments were not replicated in this phase (Table 3). We report here data collected during 50 d (DOY 247–297, 2002). Both alfalfa and wheatgrass were harvested twice during this time, on DOY 262 and 297.

The running ET calculations for the control lysimeters were short-term (2-d) calculations that, as noted above, may lack precision and fluctuate about the true value. Consequently, it was expected that the target irrigation treatments might not be realized exactly. Table 3 also lists the "actual" irrigation treatment, $f = I/\mathrm{ET}$, where I is the cumulative Phase 2 (DOY 247–297) irrigation in a particular lysimeter and ET is the cumulative evapotranspiration measured in the corresponding control lysimeter. As shown in Table 3, the actual treatments, summed across the entire 50 d, were reasonably close to the target treatments.

RESULTS AND DISCUSSION

Evapotranspiration

Figure 3 illustrates the high levels of ET that were measured in the lysimeters. The figure shows $\mathrm{ET/ET_0}$, where ET is the evapotranspiration measured in the control lysimeters and $\mathrm{ET_0}$ is a reference evapotranspiration. The value of $\mathrm{ET_0}$ was obtained from a CIMIS weather station (California Irrigation Management Information System weather station no. 44; http://www.cimis.water.ca.gov) that provides hourly calculations of reference evapotranspiration based on a modified Penman equation that is representative of a "standardized grass" surface. The weather station is <3.2 km from the lysimeter facility. Figure 3 shows that $\mathrm{ET/ET_0} \sim 1$ in the control lysimeters immediately after harvest, but increased considerably as the crops grew, at times being >4. For the harvests depicted in Fig. 3, the canopy height at the time of harvest averaged ~63 cm for tall wheatgrass and ~56 cm for alfalfa. After harvest, the canopy height was 10 cm for both crops. Figure 3 uses short-term (2-d) calculations of ET in the volumetric lysimeters, so again it is probable that the plotted values fluctuate somewhat about the true values.

Table 2. Phase 1 experimental treatments.

Lysimeter no. Alfalfa	Lysimeter no. Tall wheatgrass	Irrigation water electrical conductivity
		dS m^{-1}
61 and 73	67 and 69	2.5
75 and 76	70 and 72	8
65 and 66	56 and 71	13
64 and 78	57 and 60	18
63 and 77	55 and 58	23
62 and 74	59 and 68	28

Table 3. Phase 2 experimental treatments.

Lysimeter no.	Irrigation water electrical conductivity	f† Target	f† Actual
	dS m^{-1}		
	Alfalfa		
76	8	0.5	0.5
64	18	0.5	0.7
74	28	0.5	0.5
61	2.5	0.75	0.7
65	13	0.75	0.8
77	23	0.75	0.7
75	8	1.0	0.9
78	18	1.0	1.0
62	28	1.0	0.9
73	2.5	»1.0	2.6
66	13	1.25	1.1
63	23	1.25	1.2
	Tall wheatgrass		
70	8	0.5	0.5
57	18	0.5	0.5
59	28	0.5	0.5
69	2.5	0.75	0.7
71	13	0.75	0.7
58	23	0.75	0.7
72	8	1.0	0.9
60	18	1.0	0.9
68	28	1.0	0.9
67	2.5	»1.0	2.7
56	13	1.25	1.1
55	23	1.25	1.1

† Irrigation depth, expressed as a fraction of evapotranspiration measured in control lysimeters (lysimeters 67 and 73).

Under standard growing conditions, $\mathrm{ET/ET_0}$ generally will not exceed 1.2 to 1.4 (Allen et al., 1998). The lysimeter crops are small, isolated stands of vegetation that are subject to "oasis" and "clothesline" effects that increase ET. As stated by Allen et al. (1998), these effects occur "where turbulent transport of sensible heat into the canopy and transport of vapor away from the canopy is increased by the 'broadsiding' of wind horizontally into the taller vegetation." Figure 46 of Allen et al. (1998) suggests that for lysimeters of the size used in our study, $\mathrm{ET/ET_0}$ may be as high as 2.5. If the data in Fig. 3 are viewed cumulatively during the two time intervals depicted (DOY 156–214 and 247–297), more precise calculations are possible and we found that $\mathrm{ET/ET_0}$ was equal to 1.6 for alfalfa and 2.1 for tall wheatgrass during DOY 156–214, and 2.4 for both crops during DOY 247–297.

Biomass Production and Salt Tolerance

Crop salt tolerance is commonly described using the Maas–Hoffman yield response function. According to this model, a crop will achieve its maximum yield when the root-zone-averaged soil salinity, quantified as the electrical conductivity of the soil saturation extract ($\mathrm{EC_e}$), is below a crop-specific threshold value A. For soil salinities above the threshold ($\mathrm{EC_e} > A$), yield is assumed to decrease linearly with increasing $\mathrm{EC_e}$ (Maas and Hoffman, 1977):

$$Y_r = 100Y/Y_{max} = 100 - B(\mathrm{EC_e} - A) \qquad [3]$$

where Y_r is the relative yield (expressed as a percentage), Y is the absolute yield, Y_{max} is the "maximum"

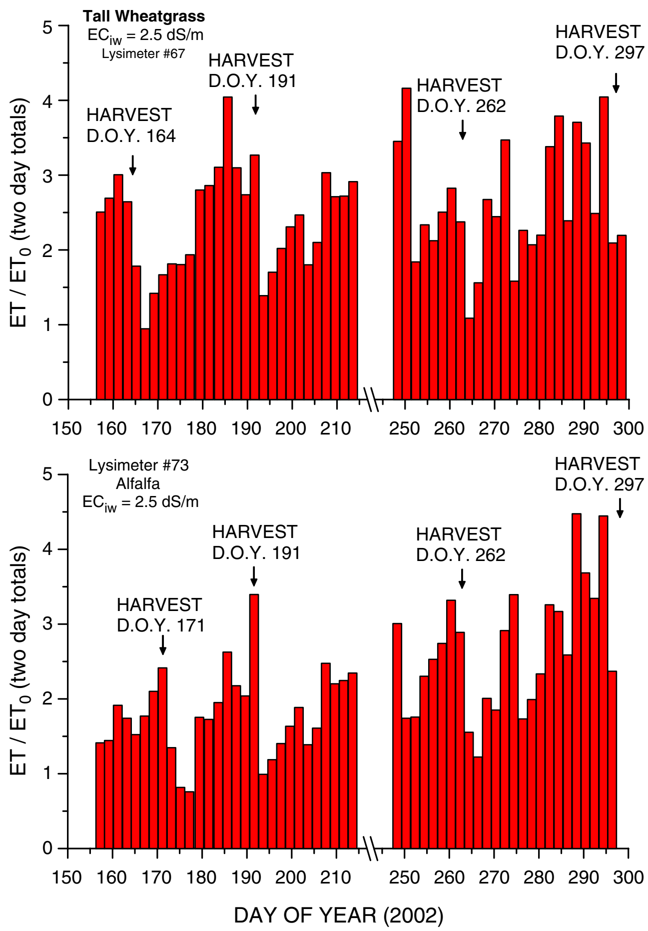

Fig. 3. Measured evapotranspiration (ET) in two well-watered lysimeters, expressed as the ratio of the measured ET to a reference ET_0 calculated using a modified Penman equation.

yield that would be obtained under optimal growing conditions, A is the threshold salinity, and B is the decrease in yield per unit increase in salinity (expressed as a percentage). Maas (1990) reported values of $A = 7.5$ dS m^{-1} and $B = 4.2\%$ m dS^{-1} for tall wheatgrass, and $A = 2.0$ dS m^{-1} and $B = 7.3\%$ m dS^{-1} for alfalfa.

Because we measured yield vs. the electrical conductivity of the irrigation water (EC_{iw}) rather than vs. EC_e, we cannot estimate Maas–Hoffman parameters directly. We can, however, make a comparison of our data with published salt-tolerance parameters by specifying a relationship between EC_e and EC_{iw}. Because of the high leaching fraction (between ~50 and 75%) and high irrigation frequency (every other day) maintained in Phase 1, we assume that the water content remained near field capacity and that the EC of the in situ soil water at field capacity (EC_{fc}) was approximately equal to that of the irrigation water, $EC_{fc} \approx EC_{iw}$. A common approach is to assume that when the water content is near field capacity, EC_{fc} is a simple multiple of the root-zone-averaged soil salinity: EC_{fc} $(=EC_{iw}) = k_{EC}EC_e$ (Ayers and Westcot, 1985; Rhoades, 1992). The Maas–Hoffman model then becomes

$$Y_r = 100Y/Y_{max} = 100 - B'(EC_{iw} - A') \qquad [4]$$

where $A' = k_{EC}A$ and $B' = B/k_{EC}$. Given the coarse texture of the soil in the lysimeters, it is reasonable to assume that k_{EC} was between 2 and 4.

Estimates for A' and B' were determined using nonlinear least-squares optimization to fit Eq. [4] to the dry-weight yield vs. EC_{iw} data. For each crop, a single fit was obtained using data from five consecutive Phase 1 harvests. The parameters A' and B' were assumed to be constant across the five harvests while the maximum yield was allowed to vary from harvest to harvest (van Genuchten, 1983). Thus, seven parameters were fitted for each crop: A', B', $Y^{(1)}_{max}$, …, $Y^{(5)}_{max}$. The fittings were done using Mathematica's nonlinear regression package (Wolfram Research, 2003). The fitted salt-tolerance parameters and 95% confidence intervals were $A' = 2.2 \pm 1.6$ dS m^{-1} and $B' = 2.9 \pm 0.29\%$ m dS^{-1} for tall wheatgrass, and $A' = 12 \pm 2.6$ dS m^{-1} and $B' = 4.5 \pm 0.96\%$ m dS^{-1} for alfalfa.

Figure 4 shows plots of the cumulative relative yields vs. EC_{iw} data and the fitted yield response curves. Also shown are a range of yield response curves calculated using the Maas–Hoffman parameters (A and B) reported in the literature (values noted above). The lower bound was obtained using $k_{EC} = 2$ to convert A and B to

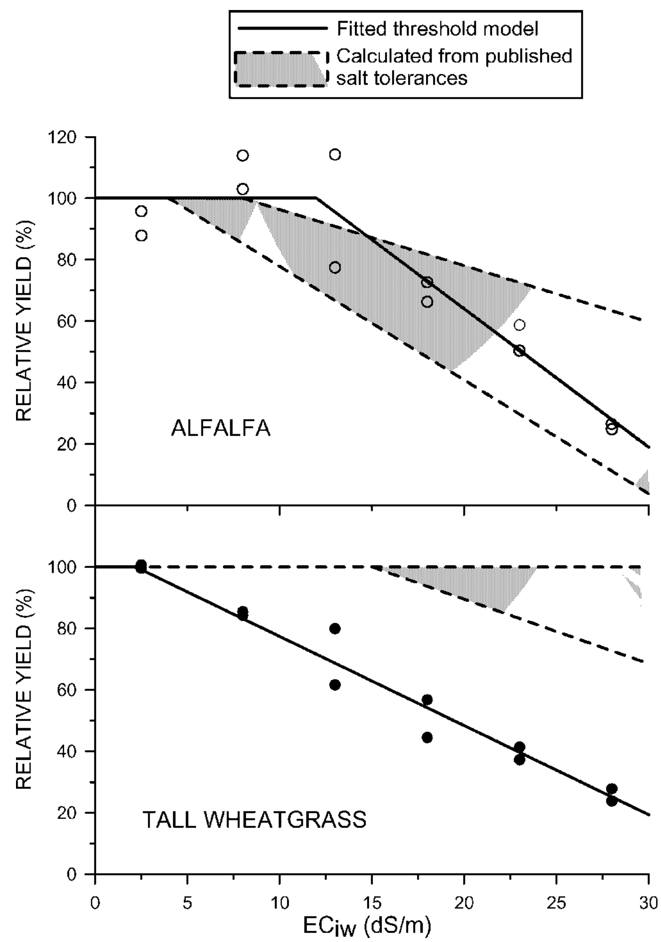

Fig. 4. Phase 1 measured relative yields as a function of the electrical conductivity (salinity) of the irrigation water (EC_{iw}). Data are cumulative totals collected during five harvests. The shaded areas represent the range of yields expected based on published salt tolerances.

A' and B', whereas the upper bound used $k_{EC} = 4$. The relative yield data shown in Fig. 4 were obtained by summing the yield in each lysimeter across the five Phase 1 harvests and dividing that total by the sum of the five fitted maximum yields.

It is apparent from Fig. 4 that the salt tolerance we observed for tall wheatgrass did not agree very well with the published tolerance. Tall wheatgrass is reported in the literature to have a high threshold, $A = 7.5$ dS m^{-1}, which (assuming $2 < k_{EC} < 4$) corresponds to an EC_{iw} threshold (A') between 15 and 30 dS m^{-1}. Yet the wheatgrass data in Fig. 4 show substantial decreases in yield at much lower salinities. For example, yield decreased nearly 20% between $EC_{iw} = 2.5$ and $EC_{iw} = 8$ dS m^{-1} (Fig. 4). In fact, while the tall wheatgrass data in Fig. 4 show an approximately linear decrease in yield with increasing salinity, it is not possible to discern a threshold because there were not (at least) two EC_{iw} treatments below the threshold. Diagnostic information from the regression analysis package indicated that the tall wheatgrass threshold parameter and confidence intervals ($A' = 2.2 \pm 1.6$ dS m^{-1}) were poorly determined by the data. Regardless, it is clear that the observed tall wheatgrass threshold was significantly lower than reported in the literature. The fitted slope parameter value was larger than reported in the literature ($B' = 2.9 \pm 0.29$% m dS^{-1} fitted vs. an expected value of $B' = 1.1$–2.1% m dS^{-1}), also indicative of a lower-than-expected salt tolerance. In general, it is thought that plant salt tolerance decreases in warm and dry conditions where evaporative demand is high (Shalhevet, 1994; Maas and Grattan, 1999), and we may speculate that the high ET rates observed in this study contributed to the unexpectedly low tolerance.

The 'Salado' data are in better agreement with the published tolerance for alfalfa (Fig. 4). The fitted threshold parameter ($A' = 12 \pm 2.6$ dS m^{-1}) was higher than the anticipated value ($A' = 4$–8 dS m^{-1}) whereas the fitted slope parameter ($B' = 4.5 \pm 0.96$% m dS^{-1}) was reasonably close to the expected value ($B' = 1.8$–3.7% m dS^{-1}). 'Salado' is reputed to be an especially salt-tolerant alfalfa variety, which may explain the higher observed threshold and apparent ability to withstand relatively harsh environmental conditions.

Based on the fitted models in Fig. 4, one could conclude that alfalfa exhibited higher salt tolerance than wheatgrass because of the higher threshold A' and higher relative yields across all EC_{iw}. On the other hand, Fig. 5 is a plot of the same data using absolute yields instead of relative yields and it shows that biomass production was greater for wheatgrass than for alfalfa in experimental treatments with $EC_{iw} < 10$ dS m^{-1}. At higher EC_{iw}, the yield for tall wheatgrass continued to be higher than for alfalfa, although the significance of the difference is questionable given the scatter in the data and uncertainty in the fitted models. In an earlier greenhouse study (Grattan et al., 2004a; Robinson et al., 2004), biomass production was found to be greater for 'Salado' alfalfa than for 'Jose' tall wheatgrass when grown with 15 dS m^{-1} irrigation water, while production was roughly the same for the two species when grown with 25 dS m^{-1} water. The 15 dS m^{-1} finding from the earlier study is not confirmed by our study, where biomass production for tall wheatgrass was equal to or in excess of that for alfalfa.

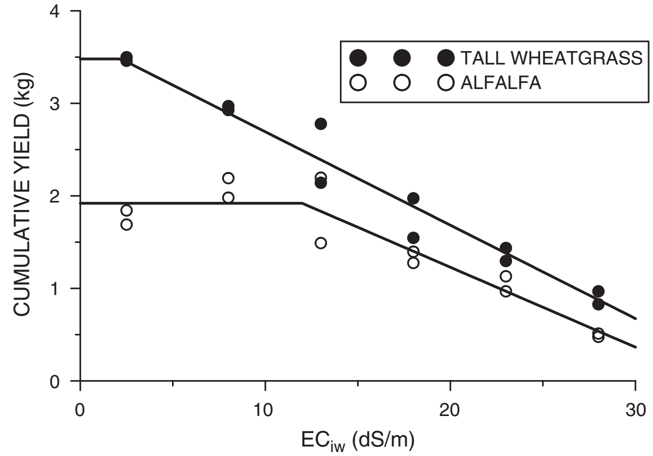

Fig. 5. Phase 1 measured yields as a function of the electrical conductivity (salinity) of the irrigation water (EC_{iw}). Data are the same as in Fig. 4, except in absolute instead of relative terms.

Grattan et al. (2004a) lists high biomass production, high salt tolerance, and high forage quality as being the desired characteristics of forages for drainage reuse systems. All of these characteristics are influenced by a variety of environmental factors (Maas, 1990). In the earlier greenhouse study, forages were grown in sand tanks that were less than half the size of the lysimeters used in this study, the water compositions were different, the irrigation frequency was not the same (three times per day vs. once every other day), and the greenhouse atmospheric conditions differed from those at the outdoor lysimeter system. Presumably, some combination of these differences in environmental conditions led to the observed relative differences in biomass production at 15 dS m^{-1}. In any event, the observed differences in crop yield serve as a reminder that crops identified as top performers in greenhouses and sand lysimeters may not necessarily perform the best under field conditions, where environmental conditions could differ significantly from the controlled conditions used in salt-tolerance trials.

Yield vs. Evapotranspiration

Figure 6 is a plot of relative cumulative yield ($=Y/Y_{max}$) vs. cumulative relative evapotranspiration ($=ET/ET_{max}$) as measured across five Phase 1 harvests. The maximums Y_{max} and ET_{max} are the average of the cumulative Y and ET measured in lysimeters with EC_{iw} below the threshold (see Fig. 4). For alfalfa, the maximums are the average of the four lysimeters with $EC_{iw} = 2.5$ or 8 dS m^{-1}; for tall wheatgrass, they are the average of the two lysimeters with $EC_{iw} = 2.5$ dS m^{-1}. In Fig. 6, the same linear regression fits both the tall wheatgrass and alfalfa data ($r^2 = 0.88$). This linear relationship can be expressed as (Stewart et al., 1977; Doorenbos and Kassam, 1979)

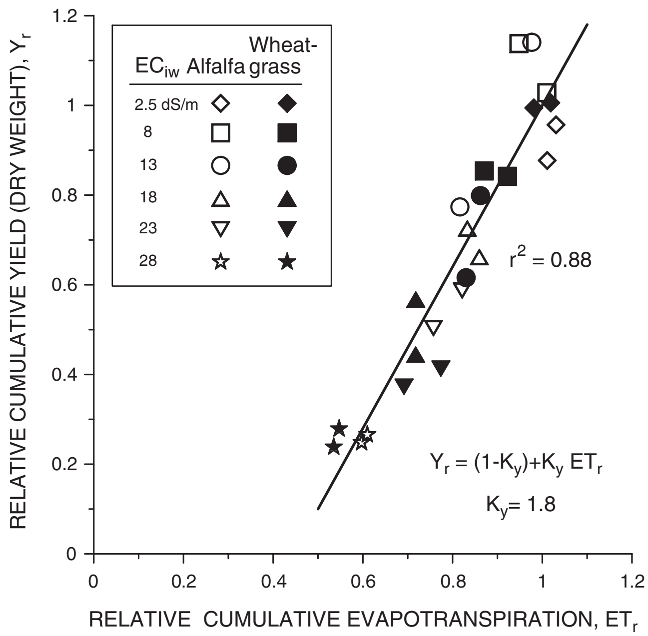

Fig. 6. Observed relationship between relative yield and relative evapotranspiration as measured in the Phase 1 experiments. K_y is the yield response factor and EC_{iw} is the electrical conductivity of the irrigation water.

$$(1 - Y/Y_{max}) = K_y(1 - ET/ET_{max}) \quad [5]$$

where K_y is called the yield response factor and is equal to 1.8 for the data presented in Fig. 6. Doorenbos and Kassam (1979) tabulated values of K_y for various crops and reported values of 0.7 to 1.1 for alfalfa. In later studies (Undersander, 1987), the ET–yield relationship for alfalfa has been shown to vary considerably from location to location and season to season, and higher values have been reported also (e.g., Undersander, 1987, Harvest 2 in 1983). Overall, though, our data indicates a higher K_y than is typically observed for alfalfa.

Most reported values of K_y are based on studies in which the ET deficit is due to deficit irrigation. Generally it has been observed or assumed that Eq. [5] holds regardless of whether the ET deficit is due to deficit irrigation or salinity stress (Katerji et al., 1998; Stewart et al., 1977), although the value of K_y may be affected by water quality, particularly if canopy development is lessened (Shalhevet, 1994). Additionally, while there are many similarities in the response of plants to drought and salinity stresses, differences also exist that could affect K_y for certain combinations of crops and water compositions, particularly when viewed over longer time periods (Shalhevet and Hsiao, 1986; Munns, 2002). Very few studies, if any, have looked at salinity-induced ET deficits using the high levels of salinity considered in this study. Extrapolating the linear fit in Fig. 6 down to zero yield suggests a large evaporative component of ET, but the relative yield–ET relationship is not expected to remain linear below ET/ET_{max} ~ 0.5 (Doorenbos and Kassam, 1979), and it is unlikely that the evaporative component was as large as extrapolation suggests; however, there was less canopy development in the high-salinity treatments, and evaporation was possibly more significant in these (abundantly watered) saline lysimeters than in ET deficit studies employing deficit irrigation (where presumably the soil surface would be drier on average). A larger evaporative component would correspond to a larger value of K_y.

As with the salt-tolerance data discussed above (Fig. 4 and 5), when the yield–ET data are viewed in absolute instead of relative terms, it is seen that ET was higher for tall wheatgrass across all treatments (data not shown).

Leaching Fraction

Figure 7 is a plot of the leaching fraction (ratio of cumulative drainage to cumulative irrigation) measured during the first 50 d of Phase 2. Recall that during Phase 2, lysimeters received varying amounts of water as prescribed in Table 3. Figure 7 shows that the leaching fraction depended on both the amount and quality of the irrigation water. For example, Fig. 7 shows that in lysimeters receiving ~0.35 m of water, the leaching fraction ranged from almost zero to as high as 0.4 depending on the EC of the irrigation water. The highest measured leaching fractions (in the range 0.5–0.65) were found in lysimeters receiving between 0.4 and 0.6 m of either 23 or 28 dS m^{-1} water. Obtaining a comparable leaching fraction with 2.5 dS m^{-1} required the application of more than twice as much water, ~1.3 to 1.4 m (Fig. 7). So while it is sometimes implied that irrigators can manage the leaching fraction by varying irrigation depths, Fig. 7 confirms that the leaching fraction is a response to both irrigation depth and water quality. In the context of drainage reuse systems, the implication is that when irrigating with highly saline water, the leaching fraction will necessarily remain high, and the percentage of recycled drainage water converted to ET may be lower than one would hope.

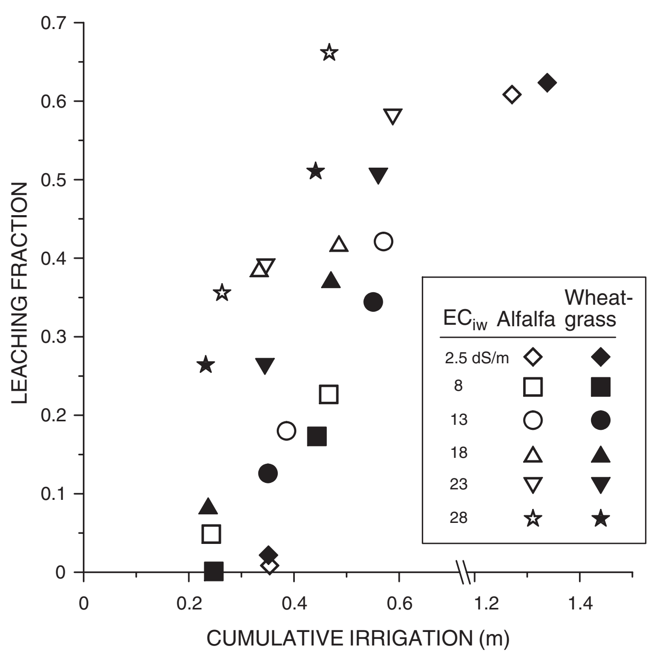

Fig. 7. Measured leaching fraction as a function of irrigation depth and electrical conductivity (salinity) of the irrigation water (EC_{iw}). Data are from Phase 2 and are 50-d cumulative totals.

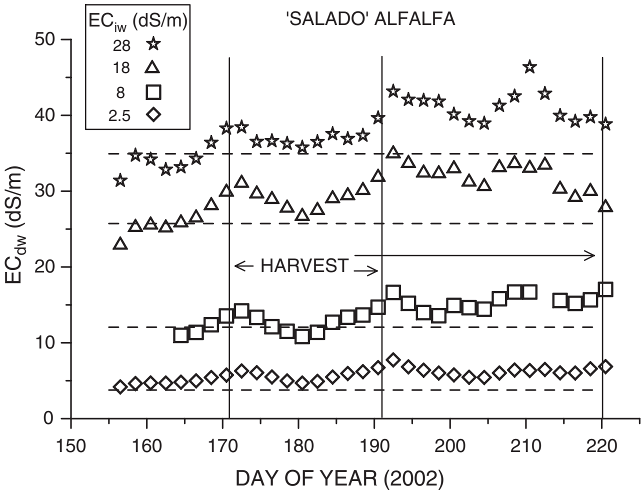

Fig. 8. Time variation of the drainage water salinity (EC_{dw}) measured in selected alfalfa lysimeters during Phase 1. The dashed lines are steady-state model calculations.

Drainage

Figure 8 shows the drainage water salinity, EC_{dw}, measured in four alfalfa lysimeters during a portion of Phase 1. During this time, irrigation was quasi-steady, with ~5 cm of water being applied every other day, except on DOY 178 when double that amount was applied. The plotted EC_{dw} data are daily averages of the electrical conductivity measured with the four-probe instrument (Fig. 1). The dashed horizontal lines in Fig. 8 are steady-state calculations for EC_{dw} based on the assumption that the salt concentration in the drainage water was equal to the concentration of the irrigation water divided by the leaching fraction (calculated for each lysimeter using cumulative irrigation and drainage totals for the time period depicted in the figure). The relationship between EC and salt concentration (sum of cations) is EC = $0.168c^{0.866}$, where EC has units of deciSiemens per meter and the salt concentration, c, has units of milliequivalents per liter (Skaggs et al., 2006).

Figure 8 shows that EC_{dw} varied in response to variations in ET, as would be expected. Before harvest when ET was increasing (Fig. 3), drainage and leaching were decreasing, leading to an increasing EC_{dw}. After harvest there was a drop in ET, an increase in drainage and leaching, and a corresponding decline in EC_{dw}. These basic trends are seen throughout Fig. 8 except for the EC_{iw} = 18 and 28 dS m^{-1} lysimeters at the DOY 220 harvest, and were evident in all other lysimeters (data not shown).

The EC_{dw} data in Fig. 8 are generally above the predictions based on steady-state calculations. The reason for this is not known. If anything, we anticipated that in the high EC_{iw} treatments, some salt might be lost to precipitation, in which case EC_{dw} should fall below the steady-state prediction. In hindsight, we believe the calibration procedure used for the four-probe instruments may have introduced some error into the EC_{dw} measurements at high EC, and we must acknowledge some uncertainty with respect to the magnitude of the measured EC_{dw}; however, we believe the temporal variations seen in the data are reflective of actual variations that occurred in the drainage water salinity, and thus can be compared in a qualitative sense with model predictions. Skaggs et al. (2006) provide a more comprehensive presentation of the drainage depth and drainage EC data.

SUMMARY

Modeling can potentially be used as a tool for designing management practices for drainage reuse operations, but at present the accuracy of model simulations is not known because of inadequate documentation of the performance of root water uptake routines under saline field conditions such as may be encountered in reuse systems. Using a volumetric lysimeter system, our objectives were to (i) examine relationships between irrigation water quality, irrigation depth, forage crop biomass production (alfalfa and tall wheatgrass), ET, drainage depth, and drainage water quality; and (ii) collect data that could be used to test a numerical simulation model.

We observed that ET in the lysimeter system was very high—ET in well-watered controls averaged more than two times ET_0. The high ET rates were attributable to oasis and clothesline effects. The extent to which the high ET rates impacted other results (salt tolerance, yield–ET relations, etc.) is not known, although it is worth noting that a significant portion of salt-tolerance data in the literature was derived from experiments using nonstandard growing conditions. In any event, the observed salt tolerance of tall wheatgrass was significantly lower than reported in the literature, while the salt tolerance of alfalfa was in reasonable agreement with reported values. The drainage data illustrated that achieving the goal of converting drainage water to ET in reuse systems is hindered by the high leaching fraction that results from irrigating with saline waters. Skaggs et al. (2006) contains a comprehensive presentation of drainage data and compares the data with model simulations.

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